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Carbon-14 wiggle-match dating of peat deposits: advantages and limitations

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ABSTRACT: Carbon-14 wiggle-match dating (WMD) of peat deposits uses the non-linear relationship between ^{14}C age and calendar age to match the shape of a series of closely spaced peat ^{14}C dates with the ^{14}C calibration curve. The method of WMD is discussed, and its advantages and limitations are compared with calibration of individual dates. A numerical approach to WMD is introduced that makes it possible to assess the precision of WMD chronologies. During several intervals of the Holocene, the ^{14}C calibration curve shows less pronounced fluctuations. We assess whether wiggle-matching is also a feasible strategy for these parts of the ^{14}C calibration curve. High-precision chronologies, such as obtainable with WMD, are needed for studies of rapid climate changes and their possible causes during the Holocene. Copyright © 2004 John Wiley & Sons, Ltd.

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KEYWORDS: ^{14}C chronologies; ^{14}C calibration; ^{14}C wiggle-match dating.

Introduction

Constructing chronologies by transforming ^{14}C ages of dated samples into 'real' calendar ages can be problematic, principally because ^{14}C age has a non-linear relationship with calendar age (see Fig. 1a). Sometimes the ^{14}C calibration curve INTCAL98 (Stuiver *et al.*, 1998), largely based on dendrochronology, shows pronounced excursions (wiggles); at other times, the slope of the ^{14}C calibration curve is almost flat (plateaux). Both phenomena result in a large range of probable calendar ages of ^{14}C dates.

Local conditions (e.g., hard-water effect, fungal contamination, choice of organic component) can cause ^{14}C ages of dated samples to appear up to several hundreds of years too old or too young (e.g., Kilian *et al.*, 1995, 2000; Shore *et al.*, 1995; Wohlfarth *et al.*, 1998; Nilsson *et al.*, 2001).

Another cause of uncertainty about the correctness of a chronology can be the decision of how to estimate ages of the non-dated levels in deposits with an unknown accumulation history, such as peat or lake sediments (e.g. Bennett, 1994). Hiatuses or changes in accumulation rate could have occurred, and should be taken into account when constructing a chronology. In some studies, for constructing a chronology ^{14}C dates are calibrated, whereas on other occasions they are not. Sometimes, a linear relationship between depth and time is assumed. In other studies an exponential or higher polynomial relation is assumed (Bennett, 1994; Kilian *et al.*, 2000) (regression, drawing the 'best' line that runs through the ^{14}C dates). Another approach is to connect all midpoints of adjacent ^{14}C dates with lines (linear interpolation), thus changing the apparent accumulation rate after each dated level.

By calibrating individual ^{14}C dates, the above-mentioned problems can result in erroneous or imprecise chronologies. With our approach of wiggle-match dating (WMD), however, we are often able to circumvent the problems mentioned above and create a more precise chronology. In this paper, we discuss WMD, and explore its advantages and limitations.

Carbon-14 calibration

In order to create a chronology, usually individual ^{14}C dates are calibrated, using software such as OxCal (Bronk Ramsey, 1998, 2000). The outcome of this calibration is a probability distribution of the ^{14}C date along the calendar axis. During periods where the ^{14}C calibration curve shows a steep decline, calibration is relatively straightforward as the resulting probability distribution on the calendar scale shows only a small range. When a ^{14}C date has the age of a plateau in the ^{14}C calibration curve, however, the resulting range of probable calendar ages can be very large (up to 350 yr for ^{14}C dates around 2400 yr BP). In addition, the same ^{14}C age often appears several times in the ^{14}C calibration curve (wiggles). If this is the case, calibration results in several optima in the probability distribution on the calendar scale.

After calibrating each individual ^{14}C date, the midpoint of the total error range (one or two standard deviations) on the calendar scale of every individual calibrated ^{14}C date is usually

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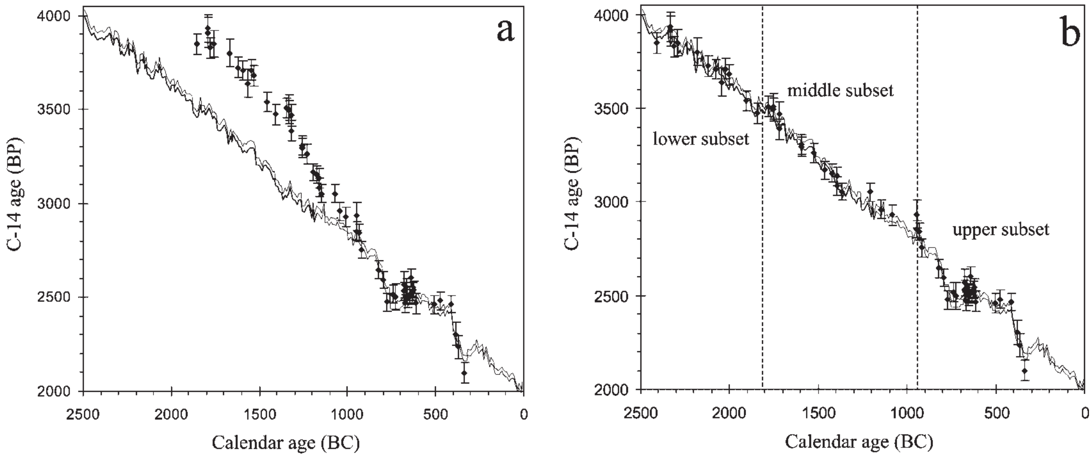

Figure 1 The ^{14}C dates of core Eng-XV (diamonds with 1 σ error bars for ^{14}C age, see Table 1; for details of the core see Blaauw *et al.*, 2003, in press) together with the relevant part of the INTCAL98 ^{14}C calibration curve (lines without symbols indicate the 1 standard deviation error range). In (a), the entire ^{14}C sequence is plotted without division into subsets. In (b), the sequence is divided into three subsets, based on information from the stratigraphy. At the two levels where the subsets have been divided, major peaks of macroscopic charcoal were found. These were considered to indicate gaps in the record. Every subset has been stretched or compressed and shifted on the calendar time axis in order to fit the ^{14}C calibration curve as well as possible. See text

taken as the most probable date. In many cases, this midpoint does not match with one of the local maxima in the probability distribution on the calendar scale.

For obtaining an approximate chronology, the approach of calibration often works well. When a more precise and high-resolution chronology is aimed at, detailed information stored in the ^{14}C calibration curve can be lost by simply calibrating.

Carbon-14 wiggle-match dating

By ^{14}C wiggle-match dating peat deposits, the wiggles in the ^{14}C calibration curve can be *used* for constructing a more precise chronology (e.g. Pearson, 1986; van Geel and Mook, 1989; Kilian *et al.*, 1995; Speranza *et al.*, 2000; Mauquoy *et al.*, 2002). The rationale behind the procedure is that plants that were growing on the surface of peat bogs recorded the same fluctuations in atmospheric ^{14}C concentrations as the trees that were used for the construction of the ^{14}C calibration curve. Wiggles found in the dendrochronologically dated ^{14}C calibration curve, caused by changes in atmospheric ^{14}C concentration, will therefore also show up in ^{14}C sequences of peat deposits. The wiggles found in a sequence can then be matched to those of the ^{14}C calibration curve, as explained below.

In order to identify wiggles in a ^{14}C sequence of a peat core, and to match them to the wiggles of the ^{14}C calibration curve, large amounts of closely spaced ^{14}C samples have to be dated. These (uncalibrated) ^{14}C-dated levels are then translated directly from their *depths* into calendar ages, assuming a linear accumulation rate. Other, more complex accumulation models could be used, but we find that in most cases the simple assumption of linear accumulation rate over limited intervals results in a satisfactory, statistically allowable fit. The assumption of linear accumulation should, however, only be made if not contradicted by, for example, stratigraphy. The sequence of ^{14}C dates is plotted together with a relevant part of the ^{14}C calibration curve. Now, by adjusting the depth scale, the sequence is stretched or compressed and shifted on the calendar age scale such that the ^{14}C ages of the sequence match those of the ^{14}C calibration curve as well as possible.

The best fit can be found using a numerical approach. The procedures of this approach are described in detail by Blaauw *et al.* (2003). In the present paper only a short description of the approach will be given. A calendar age is assigned to every ^{14}C dated level of a sequence by choosing values of the parameters α (accumulation rate in yr cm^{-1}) and β (placement on the calendar age) in the formula 'calendar age $= \alpha \times$ depth $+ \beta$'. The ^{14}C age of every sample is then compared with the ^{14}C age of the ^{14}C calibration curve corresponding with the obtained calendar age. Tens of thousands of combinations of the parameters α and β are chosen by the computer in a systematic way, and corresponding goodness-of-fit values are calculated.

The goodness-of-fit of the ^{14}C dates of the sequence with those of the ^{14}C calibration curve is measured in two ways. One is based on minimalisation of weighted squares: by adapting the parameters α and β, the smallest possible 'total vertical distance' between all ^{14}C dates of the sequence and those of the ^{14}C calibration curve is sought, taking error bars into account (cf. Pearson, 1986). The other is based on maximising the product of probability densities: the probability densities of all ^{14}C dates on the calendar age scale are determined (in the same way as individual ^{14}C dates are calibrated), the height of the probability density at the calendar age assigned to every ^{14}C dated level is then calculated, and finally all 'heights' are multiplied (P). The combination of the parameters α and β that gives the highest value of P is considered to provide the most likely chronology.

Until now single calendar year ages (point estimates) were assigned to depths of ^{14}C wiggle-match dated peat sequences (Pilcher *et al.*, 1995; Kilian *et al.*, 1995, 2000; Speranza *et al.*, 2000; Mauquoy *et al.*, 2002). Clearly, WMD cannot provide chronologies with 1-yr precision because: (i) the ^{14}C calibration curve most often has decadal resolution, (ii) ^{14}C dates are measurements with error bars, (iii) even thin peat slices (e.g. 1 cm) have accumulated in more than 1 yr, and (iv) often the assumption of a linear accumulation rate is most probably an oversimplification. Using the numerical approach mentioned above, confidence intervals can be given to WMD chronologies (Blaauw *et al.*, 2003). In all peat cores studied so far with this approach, average 1 σ calendar age confidence intervals were smaller using WMD than when calibrating individual ^{14}C dates.

Table 1 Radiocarbon AMS dating results of core Eng-XV

Name	Depth[a]	Composition[b]	^{14}C age[c] (BP $\pm$ SD)	δ^{13}C (‰)	C content (%)	GrA number
51	51–50	si	2099 ± 55	−28.03	n.d.	19 142
53	53–52	si,fl,a,c,r	2236 ± 61	−27.88	45.6	19 479
54	54–53	fl,a,c	2305 ± 63	−29.20	49.3	19 470
56	56–55	si	2465 ± 47	−25.40	43.2	18 685
60	60–59	si	2481 ± 49	−29.12	43.4	18 334
62	62–61	si	2461 ± 51	−26.33	43.2	16 475
69	69–68	si	2468 ± 55	−28.93	44.9	16 476
70A	69.5–69	si	2540 ± 46	−27.52	44.8	16 492
70B	70–69.5	sp,si	2531 ± 47	−27.31	46.3	16 493
71A	70.5–70	sc,sp	2603 ± 50	−26.30	43.8	16 495
71B-Sph	71–70.5	sc,sp	2516 ± 48	−25.97	46.2	16 496
71B-Eri	71–70.5	e	2516 ± 47	−29.13	64.1	16 506
71B-Call	71–70.5	c	2510 ± 48	−30.40	56.3	16 507
72A	71.5–71	sa,sc,sp	2495 ± 47	−24.71	45.6	16 497
72B	72–71.5	sa,sc,sp	2553 ± 47	−22.87	45.0	16 502
73A	72.5–72	sa,sc,sp	2469 ± 47	−26.94	46.2	16 503
73B-Eri	73–72.5	e	2568 ± 70	−28.56	50.9	12 764
73B-Call	73–72.5	c	2532 ± 51	−29.34	57.7	16 501
76B	76–75.5	sa,sp	2501 ± 71	−28.36	43.1	12 765
77+78	78–76	s,fl,a,r	2518 ± 50	−27.18	46.4	18 337
79+80	80–78	s,r	2476 ± 49	−24.10	45.9	18 683
81A	80.5–80	si,sa	2593 ± 45	−26.79	45.1	16 485
82+83	83–81	s,fl,c,r	2646 ± 49	−24.00	48.8	18 684
89	89–88	sa,sp	2754 ± 46	−26.23	44.9	16 483
90	90–89	sp	2843 ± 46	−25.74	43.7	16 482
91A-S.pap	90.5–90	sp	2854 ± 46	−25.73	44.7	16 481
91A-Erica	90.5–90	e	2934 ± 74	−28.66	54.8	12 766
95	95–94	sp	2929 ± 53	−23.48	46.3	16 528
97	97–96	sp	2958 ± 49	−22.56	43.3	18 329
99	99–98	sc,sa,sp	3052 ± 48	−23.51	35.5	16 477
104	104–103	sp	3053 ± 47	−23.26	45.2	16 505
105A-Sph.	104.5–104	s	3135 ± 49	−22.58	45.7	16 499
105A-R.alba	104.5–104	r	3084 ± 48	−25.20	48.3	16 509
106A	105.5–105	sc,sa	3153 ± 47	−24.16	44.7	16 486
107	107–106	sa,sp	3168 ± 46	−26.12	44.8	16 480
109	109–108	sa,sc,sp	3264 ± 52	−24.91	43.6	18 328
111-Calz	111–110	c	3294 ± 52	−30.86	56.7	16 530
111-Cal + F	111–110	c	3308 ± 53	−29.90	58.6	16 529
115-Sph	115–114	sc,sa	3389 ± 55	−26.84	52.1	16 545
115-Andr	115–114	a	3471 ± 59	−27.13	49.9	16 531
116-Sph	116–115	sc,sa	3504 ± 77	−26.22	28.3	12 763
116-Andr	116–115	a	3496 ± 53	−27.50	48.9	16 544
117-Cal	117–116	c	3509 ± 54	−27.91	53.7	16 543
121	121–120	sc	3474 ± 55	−22.68	44.4	16 541
123[d]	123–122	s	3317 ± 69	−24.50	44.5	18 677
124-mix	124–123	s,e,c	3539 ± 51	−28.08	58.0	18 327
129-Sph	129–128	s	3680 ± 54	−26.22	44.6	16 540
130	130–129	sp	3710 ± 54	−27.89	44.4	16 539
131	131–130	sp	3639 ± 74	−29.20	42.8	12 905
133	133–132	s	3706 ± 51	−26.08	42.1	18 324
135	135–134	sp	3724 ± 53	−28.06	43.2	16 535
138-Scheuch	138–137	sch	3800 ± 75	−25.50	65.5	12 760
144-Scheuch	144–143	sch	3849 ± 72	−25.80	56.3	12 759
145	145–144	sch	3829 ± 55	−24.27	49.3	16 534
146-Sph	146–145	s	3931 ± 77	−26.83	46.0	12 756
146-Andr	146–145	a	3911 ± 80	−29.99	n.d.	12 758
150	150–149	s	3848 ± 54	−32.16	46.9	16 533

[a] Depths (cm) are from bottom level to top level of sample.
[b] Composition of samples: a, *Andromeda polifolia*; c, *Calluna vulgaris*; e, *Erica tetralix*; fl, Ericaceae flowers; r, *Rhynchospora alba*; sch, *Scheuchzeria palustris*; s, *Sphagnum* spec.; sa, *S.* sect. *Acutifolia*; sc, *S. cuspidatum*; si, *S. imbricatum*; sp, *S. papillosum*. All samples are from thoroughly cleaned above-ground plant remains.
[c] Radiocarbon dates are given in ^{14}C BP (before 1950), with SD = 1 standard deviation confidence interval.
[d] Sample 123 was rejected (it was an outlier and its δ^{13}C-AMS value was extremely negative; an indication that the sample was too small for successful analysis).

The success of WMD depends on the shape of the ^{14}C calibration curve during the period considered. All high-resolution WMD peat cores published to date focused on periods with major wiggles in the ^{14}C calibration curve (Kilian *et al.*, 1995, 2000; Speranza *et al.*, 2000; Mauquoy *et al.*, 2002). During major wiggles, precision obtained by WMD can be high. However, during some periods of the Holocene, the ^{14}C calibration curve shows less pronounced excursions. As a consequence, in these cases WMD does not necessarily result in a unique solution; large ranges of possible accumulation rates and positions on the calendar scale are possible. Although during such periods WMD is less successful, precision is still higher than with calibration of individual ^{14}C dates (Blaauw *et al.*, 2003).

For long sequences, the assumption of a constant accumulation rate for the entire sequence of radiocarbon dates often results in an unsatisfactory wiggle-match. In these cases it is necessary to divide the sequence into separate sections that can be assumed to have had approximately constant accumulation rates. Subsets of ^{14}C dates from each section can then be wiggle-matched separately. The division of the subsets should be based on events in the stratigraphy, for example, indications of hiatuses, or changes in lithology, pollen concentration or bulk density.

Wiggle-match dating allows the recognition of a ^{14}C reservoir effect. If necessary, a correction can be made for such an effect. Kilian *et al.* (1995) found that high-resolution sequences of ^{14}C bulk dates of raised bog peat often follow the shape of the ^{14}C calibration curve, but can be matched only when a reservoir effect (^{14}C dates appear up to several centuries too old) is taken into account. The same appears to be true for ^{14}C dates of *Sphagnum* samples that are not 100% cleaned of, for example, rootlets or fungal remains (Kilian *et al.*, 1995, 2000; Speranza *et al.*, 2000). It would not have been possible to identify this reservoir effect if the ^{14}C dates had been calibrated instead of wiggle-matched. Recognition of a reservoir effect is important, because calibration of dates having a reservoir effect may lead to serious errors in the radiocarbon chronology. In order to avoid reservoir ages, we date selected and thoroughly cleaned above-ground plant remains only. As these samples are often very small, they can be dated only with ^{14}C AMS and not with conventional ^{14}C dating.

The wiggles in the ^{14}C calibration curve as well as in ^{14}C sequences of cores from raised bog deposits were caused by changes in atmospheric ^{14}C content (Δ^{14}C). Therefore, WMD provides a *direct* temporal link between observed environmental changes in peat cores and Δ^{14}C. Van Geel *et al.* (1998), Blaauw *et al.* (in press), Mauquoy *et al.* (2002) and Speranza *et al.* (2002) show that large increases in Δ^{14}C (sharp decreases in solar activity) during the Holocene were often coeval with wet-shifts in northwest European bogs. As WMD provides a chronology based on calendar years, comparison with other precisely dated climate proxy records is possible.

A case study

As a case study, WMD results of a new high-resolution ^{14}C AMS dated sequence, Eng-XV (sampled from Engbertsdijksvenen, eastern Netherlands), are presented (Table 1; for details see Blaauw *et al.*, 2003, in press). The uncalibrated ^{14}C dates of core Eng-XV were plotted together with a part of the ^{14}C calibration curve (Fig. 1a). For calendar year period from ca. 950 to 350 BC there was a good match, but it is clear that the earlier part of the core had a lower peat accumulation rate. Moreover, there were indications of gaps (peaks of macroscopic charcoal). When the sequence was divided into subsets on the basis of stratigraphy (charcoal levels and composition of local peat-forming vegetation), and when these subsets were wiggle-match dated individually, a satisfactory, statistically acceptable composite WMD was obtained (Fig. 1b). Best fits were calculated based on the numerical approach described above.

There were many ways to wiggle-match the lower subset because during this period there were no major wiggles in the ^{14}C calibration curve (a large range of accumulation rates and shifts on the calendar time-scale was possible; Blaauw *et al.*, 2003; see Fig. 2). The range of possible wiggle-match fits for the middle subset was smaller: although there were no major wiggles or plateaux here, the ^{14}C calibration curve was steeper than during the preceding period. In this case one can speak of '^{14}C curve-matching' instead of '^{14}C wiggle-matching'. The upper subset fitted with a plateau in the ^{14}C calibration curve and with its surrounding steep parts, and showed a very good fit; here only a very small range of fits was possible.

As mentioned above, Kilian *et al.* (1995, 2000) found a reservoir effect in ^{14}C dates when samples consisted of bulk material or of above-ground macrofossils that were not 100% cleaned of ericaceous rootlets. Therefore from core Eng-XV only above-ground plant remains (such as branches, leaves and seeds) were selected and the samples were thoroughly cleaned of any visible contamination. No reservoir effect was apparent in the plateau-part of core Eng-XV; this was probably owing to the fact that the ^{14}C samples were very clean.

Several of the wet-shifts identified from changes in local vegetation composition of core Eng-XV were coeval with

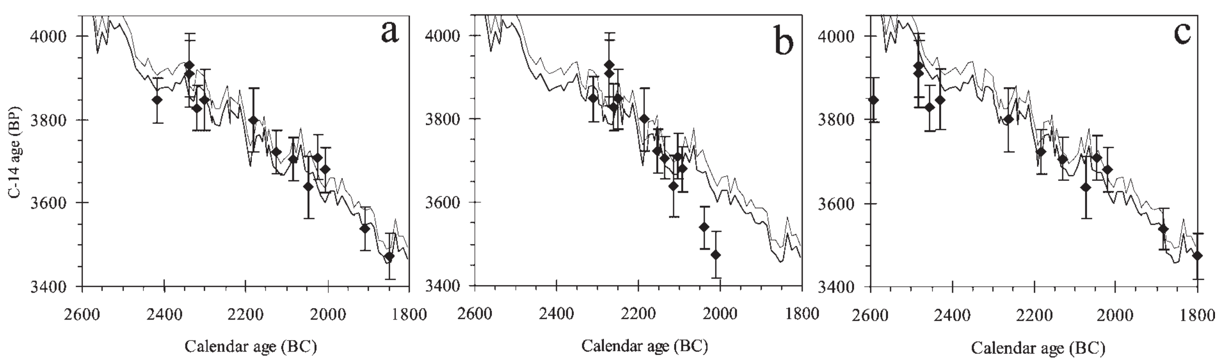

Figure 2 Several possibilities exist for ^{14}C wiggle-match dating the lower subset of Fig. 1. For explanation of symbols see Fig. 1. (a) gives the best fit, but the other solutions also are statistically possible (1 standard deviation; Blaauw *et al.*, 2003)

decreases in solar activity (recorded as peaks in the $\Delta^{14}C$ record; Blaauw *et al.*, in press).

Conclusions

When ^{14}C dates are calibrated individually, plateaux and wiggles in the ^{14}C calibration curve cause imprecise and inaccurate calendar age chronologies. However, when using WMD, these plateaux and wiggles can help in obtaining a precise and accurate chronology. Calendar ages assigned to wiggle-match dated levels are not point values; the precision of WMD chronologies can be assessed using a numerical approach.

By dating large numbers of closely spaced ^{14}C samples, it becomes possible to identify hiatuses and changes in accumulation rate in a peat deposit. With WMD, sequences are divided into subsets at occasions of such accumulation-rate changes.

The approach of wiggle-match dating works less well during periods without pronounced wiggles in the ^{14}C calibration curve. In this case there is no unique WMD solution, although precision of WMD is still higher than when individual ^{14}C dates are calibrated.

Calibration of individual ^{14}C dates that have a reservoir effect may cause serious chronology errors. However, WMD allows the recognition of a reservoir effect during periods with plateaux and wiggles in the ^{14}C calibration curve (Kilian *et al.*, 1995).

We are aware of the fact that our assumption of linear accumulation of peat sequences is an oversimplification. However, any other growth model, such as connecting midpoints of calibrated ^{14}C dates, Bayesian statistics (Bronk Ramsey, 1998), supposed constant pollen-influx (Middeldorp, 1982; Speranza *et al.*, 2000) or running higher order polynomials through a set of calibrated (e.g. Bennett, 1994) or non-calibrated (e.g. Pilcher *et al.*, 1995; Oldfield *et al.*, 1997) ^{14}C dates, also makes use of assumptions. The simple assumption of linear accumulation of a sequence over short intervals often resulted in a highly satisfactory ^{14}C wiggle-match. We claim that in such cases more 'sophisticated' growth models are not necessary as they rely on more assumptions.

A disadvantage of WMD is that the collection of high numbers of ^{14}C dates is time-consuming and expensive. Great care should be taken to select only suitable above-ground macrofossil remains and to clean the samples thoroughly (Kilian *et al.*, 1995, 2000). As the resulting samples are often very small, conventional ^{14}C dating is not possible and AMS ^{14}C dating should be used.

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References

Bennett KD. 1994. Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences. *The Holocene* **4**: 337–348.

Blaauw M, Heuvelink GBM, Mauquoy D, van der Plicht J, van Geel B. 2003. A numerical approach to ^{14}C wiggle-match dating of organic deposits: best fits and confidence intervals. *Quaternary Science Reviews*.

Blaauw M, van Geel B, van der Plicht J. in press. Solar forcing of climatic change during the mid-Holocene: indications from raised bogs in The Netherlands. *The Holocene*.

Bronk Ramsey C. 1998. Probability and dating. *Radiocarbon* **40**: 461–474.

Bronk Ramsey C. 2000. *OxCal Version 3.5*. http://www.rlaha.ox.ac.uk/orau/index.htm.

Kilian MR, van der Plicht J, van Geel B. 1995. Dating raised bogs: new aspects of AMS ^{14}C wiggle matching, a reservoir effect and climatic change. *Quaternary Science Reviews* **14**: 959–966.

Kilian MR, van Geel B, van der Plicht J. 2000. ^{14}C AMS wiggle matching of raised bog deposits and models of peat accumulation. *Quaternary Science Reviews* **19**: 1011–1033.

Mauquoy D, van Geel B, Blaauw M, van der Plicht J. 2002. Evidence from northwest European bogs shows 'Little Ice Age' climatic changes driven by variations in solar activity. *The Holocene* **12**: 1–6.

Middeldorp AA. 1982. Pollen concentration as basis for indirect dating and quantifying net organic and fungal production in a peat bog ecosystem. *Review of Palaeobotany and Palynology* **37**: 225–282.

Nilsson M, Klarqvist M, Bohlin E, Possnert G. 2001. Variation in ^{14}C age of macrofossils and different fractions of minute peat samples dated by AMS. *The Holocene* **11**: 579–586.

Oldfield F, Thompson R, Crooks PRJ, Gedye SJ, Hall VA, Harkness DD, Housley RA, McCormac FG, Newton AJ, Pilcher JR, Renberg I, Richardson N. 1997. Radiocarbon dating of a recent high-latitude peat profile: Stor Åmyrân, northern Sweden. *The Holocene* **7**: 283–290.

Pearson GW. 1986. Precise calendrical dating of known growth-period samples using a 'curve fitting' technique. *Radiocarbon* **28**: 292–299.

Pilcher JR, Hall VA, McCormac FG. 1995. Dates of Holocene Icelandic volcanic eruptions from tephra layers in Irish peats. *The Holocene* **5**: 103–110.

Shore JS, Bartley DD, Harkness DD. 1995. Problems encountered with the ^{14}C dating of peat. *Quaternary Science Reviews* **14**: 373–383.

Speranza A, van der Plicht J, van Geel B. 2000. Improving the time control of the Subboreal/Subatlantic transition in a Czech peat sequence by ^{14}C wiggle-matching. *Quaternary Science Reviews* **19**: 1589–1604.

Speranza A, van Geel B, van der Plicht J. 2002. Evidence for solar forcing of climate change at ca. 850 cal BC from a Czech peat sequence. *Global and Planetary Change* **35**: 51–65.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac FG, van der Plicht J, Spurk M. 1998. INTCAL98 radiocarbon age calibration, 24,000-0 cal BP. *Radiocarbon* **40**: 1041–1083.

van Geel B, Mook WG. 1989. High-resolution ^{14}C dating of organic deposits using natural atmospheric ^{14}C variations. *Radiocarbon* **31**: 151–155.

van Geel B, van der Plicht J, Kilian MR, Klaver ER, Kouwenberg JHM, Renssen H, Reynaud-Farrera I, Waterbolk HT. 1998. The sharp rise of $\Delta^{14}C$ ca. 800 cal BC; possible causes, related climatic teleconnections and the impact on human environments. *Radiocarbon* **40**: 535–550.

Wohlfarth B, Skog G, Possnert G, Holmquist B. 1998. Pitfalls in the AMS radiocarbon-dating of terrestrial macrofossils. *Journal of Quaternary Science* **13**: 137–145.